

Qualitative and Quantitative Jet Physics in Pb + Pb at LHC

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The momentum dependence of the exciting new Pb + Pb data from LHC qualitatively suggests a perturbative picture interpretation for the energy loss of high- p_T particles, but conclusions are difficult to draw due to the lack of 1) a quantitative theoretical calculation constrained by current high precision RHIC data and 2) a lack of control p + p and p + Pb data at LHC. Future measurements of identified heavy quark suppression will provide a novel qualitative tool for determining the dominant physics of the quark-gluon plasma created at RHIC and LHC.

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1. Introduction

The QCD Lagrangian is known and well verified by particle experiments over many orders of magnitude [1–3]. But just as the collective behavior of electrically charged objects—take for instance the phase diagram of water—is far from obvious given the QED Lagrangian, the bulk dynamics of QCD are not well understood [4]. With the Relativistic Heavy Ion Collider (RHIC), the Large Hadron Collider (LHC), and the soon-to-be-running Facility for Antiproton and Ion Research (FAIR) facilities the world scientific community has a novel opportunity to experimentally explore the state of the universe a few microseconds after the Big Bang and the phase transition from the usual, confining hadronic matter to deconfined quarks and gluons by colliding heavy nuclei, such as gold and lead, at near the speed of light. In particular rare high momentum partons, those that produce jets of particles, provide the most direct probe of the fundamental degrees of freedom in the new phase of QCD matter created at a few times the transition temperature, T_c , at these cutting-edge facilities [5–7]. Fig. 1 shows a cartoon of the energy loss of these high- p_T probes as they propagate through a deconfined plasma of quarks and gluons in (a) completely perturbative—calculable via the methods of perturbative QCD (pQCD)—and (b) completely nonperturbative—calculable via the methods of AdS/CFT—pictures. The goal, then, is to compare theoretical predictions to data to determine the properties of the quark-gluon plasma created in heavy ion collisions.

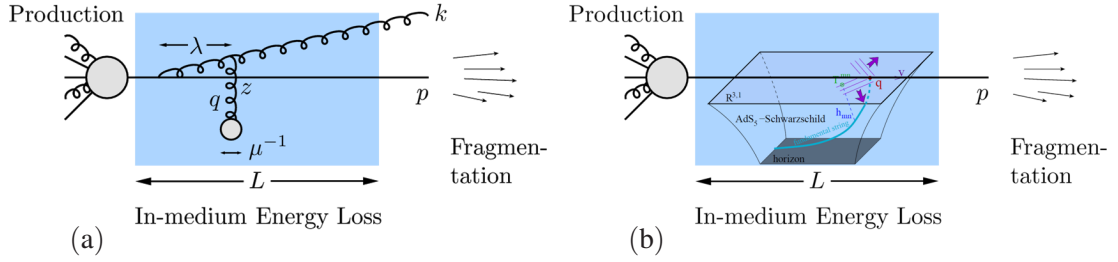


Figure 1: Cartoon of the production, in-medium energy loss, and fragmentation processes that may occur using (a) pQCD for in-medium energy loss or (b) AdS/CFT for in-medium energy loss for a high- p_T parton produced in a heavy ion collision. Figures adapted from [8] and [9].

2. Results

The suppression of high- p_T particles in heavy ion collisions is usefully expressed in terms of R_{AA} : the ratio of measured yield in nucleus-nucleus ($A + A$) collisions divided by the yield in $p + p$ collisions scaled by the expected number of $p + p$ collisions in an $A + A$ collision. Extracting information from R_{AA} , and suppression observables in general, is made nontrivial by the many physics processes—some of which are interesting in their own right—that are effectively integrated out. Of greatest import for our discussion is the initial distribution of high- p_T quarks and gluons in both coordinate and momentum space. At RHIC, reference spectra from $p + p$ collisions at the same \sqrt{s} as in $Au + Au$ collisions [10, 11] allow for a precise measurement of R_{AA} [10, 12] and constrain the initial quark and gluon spectra; there is also abundant evidence from the $d + Au$ collision data that at midrapidity the initial high- p_T partonic spectrum is not significantly modified from that in $p + p$ collisions [13, 14], and direct photon measurements reassure us that the binary distribution

from a Glauber model approximates well the number of hard proton-proton-like collisions in a heavy ion event [15].

These measurements do not yet exist at LHC, critically limiting the precision of—and our ability to interpret—the recent R_{AA} results [16], shown in Fig. 2 (a). First, there is no reference p + p data, which leads to about a factor of 2 p_T -dependent systematic uncertainty in the normalization of the reported R_{AA} . Second, there is no “control measurement” from a p + Pb run. This control measurement is crucial as there are predictions of a significant *initial state* suppression of high- p_T particles due to unitarizing effects in the initial gluon parton distribution function [17]; see Fig. 3 (a). Although not shown in that work, these effects should be x and Q^2 dependent (the effects should disappear by $p_T \sim 25 - 50$ GeV/c) naturally introducing a rise in R_{AA} as a function of p_T , perhaps similar to that seen currently in the data. The ATLAS measurement [18] consistent with a lack of suppression in its 38 Z boson candidates is encouragingly suggestive that the binary scaling seen at RHIC also holds at LHC, although the result is currently inconclusive due to the large systematic uncertainty and lack of statistics.

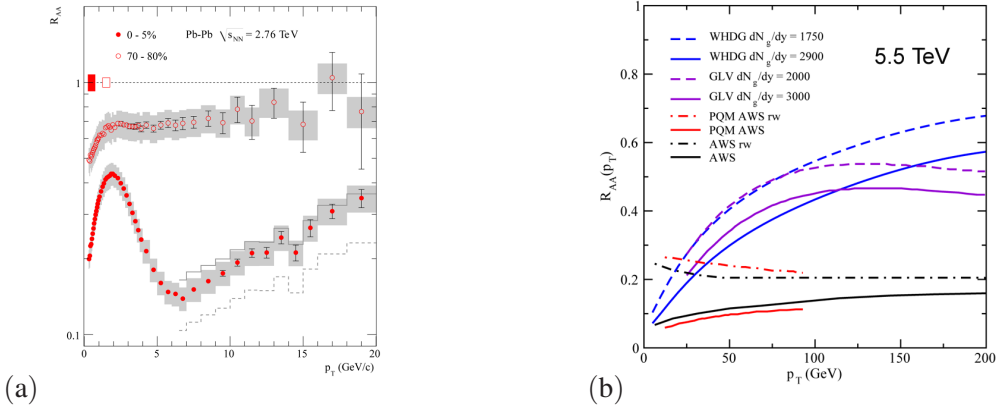


Figure 2: (a) Measured R_{AA} of charged hadrons at 2.76 TeV at LHC [16]. (b) Predictions from the WHDG energy loss model [19] for the R_{AA} of pions at 5.5 TeV [20].

There is currently debate over even a qualitative understanding of the energy loss mechanism(s) in a QGP [21–24]. Current pictures assume that either all interactions are strongly-coupled, some are strong and some are weak, or that all interactions are weak (see [7, 21] and references therein). It is worth noting, though, that none of the purely perturbative approaches quantitatively describes *simultaneously* any two single particle high- p_T observables at RHIC.

Nevertheless, the new ALICE data [16] shows a feature that appears strikingly similar to what one would expect from pQCD-based energy loss: R_{AA} rises significantly as a function of p_T . One expects a rise as a function of momentum as the fractional energy loss of a high- p_T parton goes as $\varepsilon \sim \log(p_T)/p_T$ [25], where the final momentum, p_T^f , is related to the initial momentum, p_T^i , by $p_T^f = (1 - \varepsilon)p_T^i$. If particle production is well approximated by a power law, $dN/dp_T \sim p_T^{-n}$, then $R_{AA} \sim \langle (1 - \varepsilon)^{n-1} \rangle$ [26]. The suppression at RHIC is flat within the uncertainty of the experiment [12]. If the picture of perturbative energy loss is correct, this flatness is due to a coincidental cancellation between 1) the fraction of high- p_T gluons to quarks, 2) the hardening of the production spectrum as a function of p_T , and 3) the decrease in energy loss as a function of p_T . At LHC, the production spectrum is much flatter than at RHIC while energy loss still decreases with p_T ; this then

would lead to an R_{AA} that increases with p_T . One can see from Fig. 2 (b) that that is exactly what we find for the WHDG model of pQCD-based energy loss we study here.

Furthermore, ALICE reports [27] a factor ~ 2.2 increase in the central charged particle multiplicity at LHC compared to RHIC. Assuming that the quark-gluon plasma medium density scales with charged particle multiplicity, it becomes a quantitative question whether an energy loss calculation can simultaneously describe the R_{AA} normalization at both RHIC and LHC.

An exciting future measurement is of the ratio of suppression patterns of charm and bottom quarks, R_{AA}^c/R_{AA}^b , as a function of p_T , shown in Fig. 3 (b). One readily notices how the interplay of mass and momentum scales, very different for perturbative and AdS/CFT energy loss calculations, manifests itself: in perturbative calculations the momentum loss per unit time scales as $dp_T/dt \sim -LT^3 \log(p_T/M_Q)$ whereas in the AdS/CFT calculations $dp_T/dt \sim -(T^3/M_Q^2)p_T$, where L is the pathlength traversed by the high- p_T parton, T is the temperature of the plasma, and M_Q is the mass of the heavy quark.

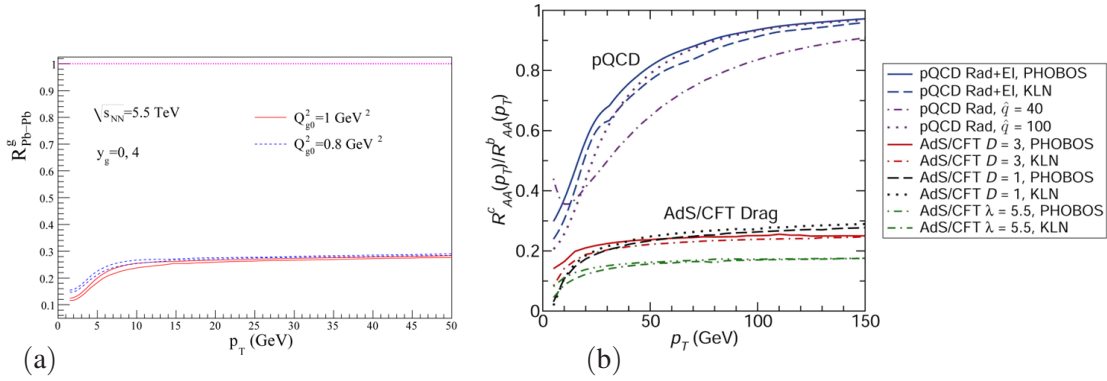


Figure 3: (a) Predictions of the suppression of gluons in top energy Pb + Pb LHC collisions from initial state effects *only* [17]. (b) The ratio of charm to bottom R_{AA} should provide a clear indication of the dominant physics of high- p_T energy loss [21].

3. Conclusions and Outlook

A new era in heavy ion physics started on November 8th, 2011 when LHC began colliding lead nuclei at $\sqrt{s_{NN}} = 2.76$ TeV, an unprecedented center of mass energy. While the initial high- p_T results have qualitative features that appear to reflect the dominance of perturbative physics, one must quantitatively compare theoretical predictions to data at both RHIC and LHC energies simultaneously. However, even before making this comparison, it is clear that even a qualitative scientific conclusion based on the measured suppression of charged hadrons will be difficult to reach due to the influence of possibly very large, currently experimentally unconstrained initial state effects and to the large systematic uncertainty in the initial spectrum of high- p_T particles. Future measurements from p + p and p + A runs at the same $\sqrt{s_{NN}}$ will greatly improve the ability for the community to reach a scientific consensus; future measurements of heavy quark suppression at LHC will provide a novel qualitative tool for investigating the gross properties of the quark-gluon plasma, such as whether the medium is best described as a strongly coupled fluid or a weakly coupled plasma.

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